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This report describes research progress in three areas: (1) the perception of complex sounds, including tonal sequences and bursts of "frozen" gaussian noise; (2) models for the discrimination of complex sounds; and (3) the perception of speech sounds, under various degrees of stimulus uncertainty and levels of training. Major accomplishments during this period include: (a) the finding that the ability to detect very small frequency changes in single components of tonal sequences, previously assumed to be accomplished only after lengthy training on the specific discrimination task in question, is largely the result of familiarity with the stimulus and is relatively independent of the manner in which that familiarity was acquired; (b) the previously described PTD rule for auditory pattern discrimination predicts the discrimination of changes in temporal as well as spectral properties of patterns, and (c) a new model of auditory pattern discrimination that combines elements of Jeffress' leaky-integrator and the Durlach-Braida equalization-cancellation models is quite successful in describing the results of noise-burst discrimination experiments, including the "PTD" phenomena mentioned above.

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The following progress report describes work accomplished under the support of AFOSR Grant No. F49620-92-J-0506DEF between September 15, 1992 and September 15, 1993. Two independent laboratories at Indiana University contributed to this work, the Hearing and Communication Laboratory in the Department of Speech and Hearing Sciences, directed by C. S. Watson, and the Auditory Research Laboratory in the Department of Psychology, directed by D. E. Robinson.

ABSTRACT

This report describes research progress in three areas: (1) the perception of complex sounds, including tonal sequences and bursts of "frozen" gaussian noise; (2) models for the discrimination of complex sounds; and (3) the perception of speech sounds, under various degrees of stimulus uncertainty and levels of training. Major accomplishments during this period include: (a) the finding that the ability to detect very small frequency changes in single components of tonal sequences, previously assumed to be accomplished only after lengthy training on the specific discrimination task in question, is largely the result of familiarity with the stimulus and is relatively independent of the manner in which that familiarity was acquired; (b) the previously described PTD rule for auditory pattern discrimination predicts the discrimination of changes in temporal as well as spectral properties of patterns, and (c) a new model of auditory pattern discrimination that combines elements of Jeffress' leaky-integrator and the Durlach-Braida equalization-cancellation models is quite successful in describing the results of noise-burst discrimination experiments, including the "PTD" phenomena mentioned above.

Scientific Goals

The goals of the project are essentially unchanged from those described in our grant proposal. We continue to pursue several lines of experimentation with complex (non-speech) auditory patterns and recently have been extending this work to stimuli with more complex frequency spectra than the pure tones used to create the auditory patterns employed in most of our previous research. One complex spectrum we have begun to investigate is the "profile" stimulus, developed by Green and colleagues. Our extension of this work has been to dynamically varying profiles, and to a study of the detectability of intensity increments that may occur at various times during the presentation of a static profile stimulus. Principles of auditory perception established in this research may assist in predicting the discriminability of significant sounds in the environment, and in designing perceptually salient and identifiable auditory warnings and other signals.

Research Summaries

A. Tonal Sequences.

1. *The proportion-of-the-total-duration (PTD) rule holds for duration discrimination.* Kidd, Watson

In previous work, we demonstrated that *frequency* resolving power for each individual component of an unfamiliar sequence of tones increases with the component's proportion of the total sequence duration (Kidd & Watson, 1992). This work has now been extended to the case of *duration* discrimination. In this case, the dimension affected by changes in PTD (i.e., time) is also the primary dimension of variation within the patterns, as well as the dimension to which listeners must attend to perform the task. Listeners were asked to detect a change in the duration of a single tone in a five-tone pattern using a modified two-alternative forced choice procedure. Target-tone durations were determined by the PTD value (0.1, 0.2, or 0.4) and the total pattern duration (250 msec or 750 msec). Context-tone durations were determined randomly on each trial. A single frequency pattern, consisting of a sequence of ascending frequencies, was used throughout the experiment. The pattern of results obtained after several thousand training trials was essentially the same as that found in the frequency-discrimination experiments. Increases in the proportion of the total pattern duration occupied by the target tone consistently resulted in lower duration-discrimination thresholds.

2. *Use of the psychophysical method of adjustment in tonal pattern discrimination.* Watson, Kidd, Aimee Surprenant, Ward R. Drennan

A difficulty in tonal-pattern research is that several thousand trials are typically required to approach asymptotic discrimination performance under minimal-uncertainty testing conditions. One solution to this problem is to use the method of adjustment to determine thresholds, rather than a forced-choice psychophysical method. In this study the extremely brief times that are required for a listener to achieve perceptual isolation for single components of a multi-tone patterns using the method of adjustment instead of a forced-choice method (minutes as opposed to hours) were demonstrated. A quantitative criterion for "perceptual isolation" is reached when a frequency match is made that is as close to the standard as can be achieved when the standard and variable tones are both presented in isolation, rather than in pattern contexts. Not all adjustments are this accurate, however. The most useful distinction between difficult and easy adjustments is shown to be the percent of all the adjustments, for a given combination of target and context tones, that meet this perceptual-isolation criterion.

3. *Properties of the structure of multi-tone sequential patterns that determine the difficulty of perceptually isolating single target components.* Watson, Kidd, Aimee Surprenant, Ward R. Drennan

A method of adjustment was used to establish the importance of each of several structural properties of the context tones, in nine-tone sequences, in determining the perceptual isolability of target components. Successful "perceptual isolation" of a target tone was assumed to be achieved when frequency matches were as accurate as those achieved for tones presented in isolation, generally meaning matching errors of less than 1%–2% for the 50-ms tones in these sequences. The context property that was found to primarily affect the frequency matches was the separation, in Hz, between the target tone and both the local and (to a lesser degree) the remote context tones. Other than its bandwidth, the form of the local pitch contour (the target tone plus the single tones immediately before and after it) had no clear effect on the ability to "hear out" the target tone, i.e., whether the local context was ascending, descending, concave up, or concave down. The contours of the remote context tones (first and last three in the patterns) likewise had no effect on performance.

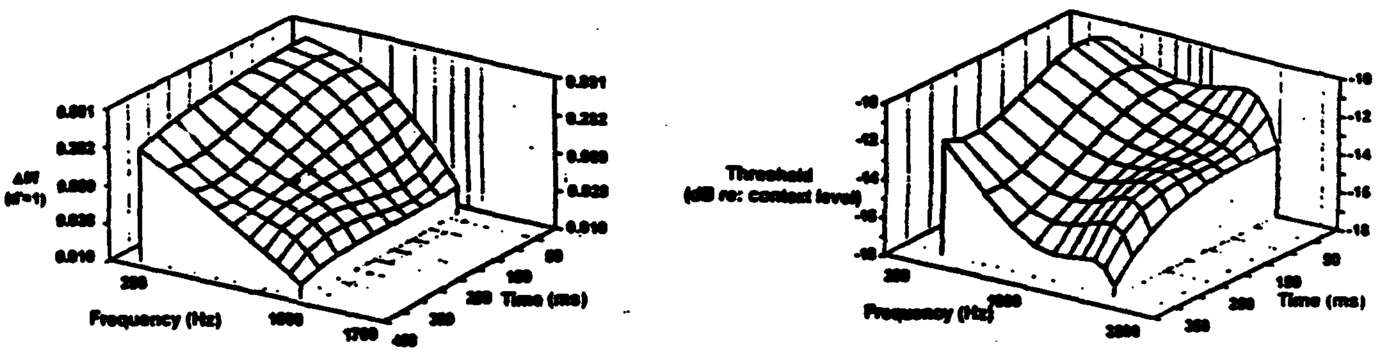
Performance ranged from 25% target tones isolated for the most difficult conditions to 90% for the easiest.

B. "Profile" Stimuli.

1. *Effects of spectral and temporal uncertainty on the detection of increments in the level of individual tonal components of "profile" stimuli.* Watson, Xiafeng Li.

In a modification of previous profile discrimination experiments (summarized in Profile Analysis , D. M. Green, Oxford University Press, 1988), intensity increments were introduced, in random order, at one of ten temporal positions during the overall duration of eleven-tone profiles, and at one of the eleven frequencies (i.e., a medium level of stimulus uncertainty). The tonal components were equi-log spaced, and five different component ranges were investigated. Differential detectability of the intensity increments over the spectral-temporal ranges of the profiles is remarkably similar to the temporal and spectral distribution of selective attention to individual tonal components of multi-tone patterns (Watson and Li, 1992). Figure 1 illustrates these results for one frequency range of the profile stimuli, and also shows frequency discrimination data for tonal patterns in a similar range, from Watson, Kelly, and Wroton (1976). In contrast to the tonal-pattern experiments, when the intensity-increment task was repeated under minimal-uncertainty conditions, performance improved very little compared to that measured under higher uncertainty. It seems likely that the reason is that the large effects of stimulus uncertainty are obtained only when the contextual components as well as the spectral-temporal targets are varied from trial to trial.

Figure 1. Similarity between the distribution of selective attention for tonal sequences (left: from Watson et al., 1976) and for a profile stimulus (right: from Watson and Li, 1992).



C. Gaussian-noise Stimuli.

1. *Discriminability of noise samples.* Rickert and Robinson

Our recent work has continued to utilize a two-interval same-different task in which human listeners are asked to discriminate between trials on which a sample of Gaussian noise is presented twice and trials on which two different samples are presented. The main goal has been to determine whether the effect of temporal position reported by Fallon and Robinson [J. Acoust. Soc. Am., 92, 2630-2635 (1992)] depends upon the bandwidth of the stimulus. For our initial investigation, we compared performance in a broadband condition (100 - 3000 Hz) with performance in a narrowband condition (450 - 550 Hz). The spectral level of the noise was held constant at 50 dB SPL in both conditions. As in the previous studies, psychometric functions were generated by varying the duration of a segment of noise during which the sample presented in the first interval is uncorrelated with the one presented in the second interval. It should be emphasized that, technically, it is the expected value of the cross-correlation of that segment computed across samples that is equal to zero. Thus, any pair of samples presented on a different trial may have non-zero cross-correlation. In addition, the results reported here were obtained using free running noise, with new samples generated on each trial. In separate experimental sessions the uncorrelated segment occurred at the beginning, in the middle, or at the end of the samples.

The results for the broadband condition may be summarized as follows:

a) Discriminability of completely uncorrelated samples depends on the overall duration. The data show that performance is generally best for a 50 ms duration and is poorer at both shorter (10 and 25 ms) and at longer (150, 200 and 400 ms) durations. This result agrees closely with one reported by Hanna [Percept. Psychophys. 36, 409-416 (1984)].

b) Discriminability is best when changes occur at the end of the sample and is poorest when changes occur at the beginning. This result is consistent with Fallon and Robinson's (1992) result. For example, based on the average data of three subjects for the 50 ms duration, we estimate that d' = 1.0 requires only about 4.5 ms for the end condition as opposed to 15.5 ms for the beginning condition. A complete summary of the average data obtained in the broadband condition for three durations is given in Table 1. Each entry is an estimate of the ratio of the duration of the uncorrelated segment to the total duration necessary to achieve a fixed level of performance.

TABLE 1

	Beginning		Middle		End	
Duration	d'=1	d'=2	d'=1	d'=2	d'=1	d'=2
25 ms	0.31	0.61	0.15	0.43	0.07	0.17
50 ms	0.31	0.62	0.14	0.42	0.09	0.20
150 ms	0.40	0.67	0.29	0.59	0.16	0.37

c) Previous data for noise samples (Fallon and Robinson, 1992) and for tonal sequences (Kidd and Watson, 1992) indicate that the ratio of the duration of the target segment to the total duration necessary to achieve a fixed level of performance is approximately constant. This has been referred to as the proportion-of-total-duration (PTD) Rule (Kidd and Watson, 1992). In our most recent experiments, however, we observe a small but consistent departure from the PTD Rule in that the ratio must be increased slightly as overall duration is increased. For example, from Table 1, the value of the ratio necessary for d' = 1.0 is 0.07, 0.09 and 0.16 (25, 50, and 150 ms, respectively) for the end, 0.15, 0.14 and 0.29 for the middle, and 0.31, 0.31 and 0.40 for the beginning.

d) Despite the fact that the ordering of the psychometric functions for temporal position is the same for durations ranging from 25 to 150 ms, it appears that the magnitude of this effect may decrease at longer durations. Our preliminary data with 400 ms samples show an advantage for the end condition but little difference in performance between the beginning and middle conditions. Note that the performance decrement found at longer stimulus durations for uncorrelated samples cannot account for this finding.

After completing the broadband conditions, subjects were tested using narrowband Gaussian noise samples that were generated by passing an array consisting of a random binary sequence through a 512 tap FIR filter prior to digital-to-analog conversion. The results may be summarized as follows:

a) Compared to the broadband condition, there is an overall performance decrement for completely uncorrelated narrowband samples at each stimulus duration (25, 50 and 150 ms). The magnitude of this decrement is far less than would be predicted by an optimal model that assumes statistical integration (i.e., square root of the product of the bandwidth and duration).

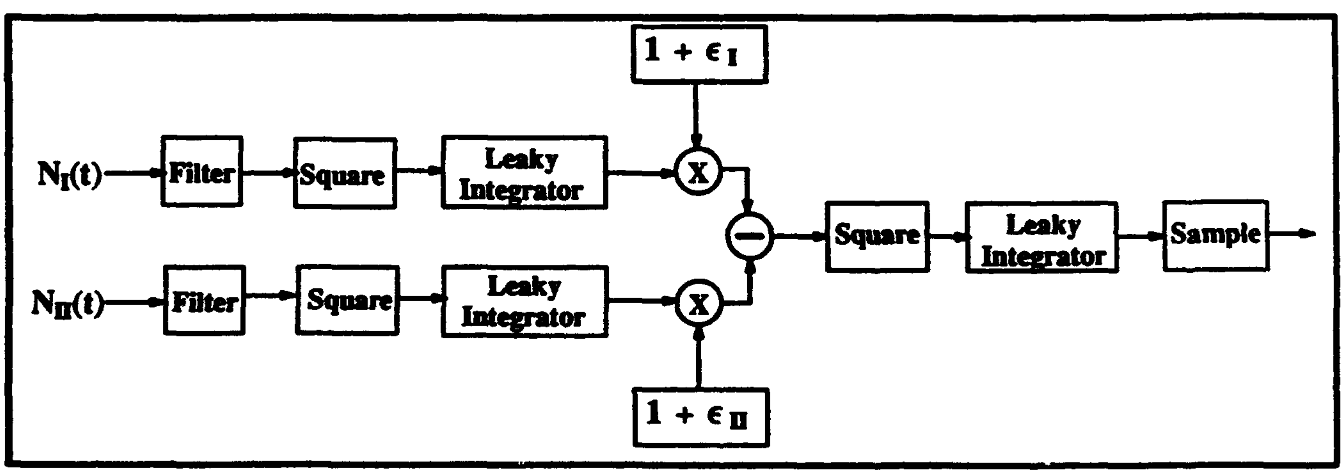
b) For a stimulus duration of 150 ms, discriminability improves as the duration of the uncorrelated segment is increased but is independent of the temporal position of the uncorrelated noise segment. Thus, the ordering of the psychometric functions that is typically found with broadband samples (E > M > B) is not evident in the narrowband condition. We plan to investigate the extent to which narrowband filtering interacts with the effects of temporal position on the discriminability of Gaussian noise samples at other stimulus durations (25, 50 and 400 ms).

D. Modeling. Robinson and Rickert

In addition to our experimental work on the discriminability of noise samples, we are continuing our efforts in developing models of the processes underlying the discrimination of complex auditory patterns. Our work has proceeded along two lines: analytical models and simulations.

We have reported on the progress of the analytical models on two occasions: at the Ottawa meeting of the Acoustical Society of America (Rickert and Robinson, 1993) and at the Dayton AFOSR conference (Robinson and Rickert, 1993). The current version of the model is shown in Figure 2. It is assumed that, in a "two-interval, same-different" paradigm, the waveform from the first interval is (1) filtered, (2) passed through a square-law device, (3) passed through a leaky-integrator, (4) jittered in amplitude with multiplicative internal noise, and (5) stored for later comparison with the output of the same sequence of operations performed on the waveform from the second interval. We chose as a comparison operation subtraction. After subtraction, the resulting waveform is squared and passed through a second stage leaky integrator. The first stages of filtering, non-linear transformation and leaky integration are commonly assumed processes in many other models of auditory processing [for examples L. A. Jeffress, J. Acoust. Soc. Am., 44, 187-203 (1968)]. The non-linearity, in our case a square-law device, is standard in many models of signal

Figure 2. A stimulus-oriented model for the discrimination of Gaussian noise samples.



N : Normal $(0, \sigma_N^2)$ ϵ: Normal $(0, \sigma_\epsilon^2)$

processing and is assumed to represent the non-linear operation of the hair cells in the cochlea. The leaky-integrator in such models is assumed to extract the envelope of the narrow-band waveform at the output of the filter. The second stage non-linearity and leaky-integration provide a smoothing or averaging of the output of the subtractor. We then assume that the output of the second stage integrator, or some monotone transform of it, serves as the decision variable. As a summary statistic, we chose the RMS of the differenced-envelopes. The model has two free parameters: the variance of the internal noise and the time constant of the integrator. The model does an excellent job of describing the data from Coble and Robinson (1992). The model also accounts for the observation reported previously that as total burst duration is varied, the duration of the uncorrelated segment required for a fixed level of performance stays in an approximately constant ratio to the total duration. This result, also found by Watson and his colleagues using tonal sequences, is a result of the approximately linear growth of the output of the second stage leaky-integrator. In addition, the model does a reasonable job of describing several other effects that are reported by Fallon in her PhD dissertation. These include the effects of decorrelation, filtering, and the introduction of temporal gaps.

One of the difficulties inherent in the analytical approach is that an accurate mathematical description of the model shown in Figure 2 is difficult to obtain. In addition, the probability distributions of the output statistic are not known. Thus, in the analytical model, we have been required to use approximations, the accuracy of which are not known. In an effort to overcome these difficulties, we have begun using computer simulations. We have implemented the stages shown in Figure 2 using MATLAB running on a DEC 5900 under ULTRIX. In this simulation the filtering and leaky integration are achieved with digital filters. The first stage non-linearity has been changed to half-wave rectification. Currently, the decision variable is the maximum output of the last stage leaky-integrator which occurs at the end of the noise burst. Although still in its early stages, this approach seems promising and suggests that the approximations in the analytical model were reasonably good, e.g. the analytical results and the simulations are in reasonable agreement.

E. Psychophysics of speech.

Previous speech discrimination studies have mainly been conducted under conditions of high stimulus uncertainty and with very little training of the listeners. While data from such studies provide valid measures of the information extracted from the speech waveforms under everyday listening conditions, they may be very poor estimates of actual acuity or resolving power for those stimuli. Several lines of research addressed the general question, what changes in the waveforms of speech can be detected under minimal stimulus uncertainty, and how is performance related to a variety of task variables?

1. *Detection thresholds for vowels*. Kewley-Port and C. Watson

In an initial study, vowel detection thresholds for normal hearing listeners were found to differ by 20 dB across ten synthetic English vowels (Kewley-Port, 1989, 1991). One model (Average Excitation which calculated the average intensity in dB over the entire excitation pattern) accounted for most of the variance in the vowel thresholds (Kewley-Port, 1991). Further studies, following the model of the tonal-pattern experiments, manipulated stimulus uncertainty for vowel sequences (Kewley-Port and Watson, 1986; Kewley-Port, 1990). Thresholds for detecting the presence of a target vowel in a sequence differed only slightly across positions within the vowel sequence, but showed a wide range, about 43 dB, from the best to the worst subject. Discrimination performance for vowel sequences is similar to that obtained for non-speech tonal patterns, in terms of the time-course of learning, differential detectability of the stimuli, effects of levels of stimulus uncertainty and unexpectedly large individual differences among the normal-hearing listeners.

2. Formant Frequency Discrimination. Kewley-Port and C. Watson.

Discrimination thresholds for formant-frequency discrimination, for F1 and F2, were obtained for ten synthetic English vowels (Kewley-Port, 1990; Kewley-Port and Watson, 1993). In general, thresholds values of ΔF as a function of formant frequency are best described as a piecewise-linear function which is constant at 14 Hz in the F1 frequency region (<800 Hz), and increases linearly in the F2 region. In the F2 region, the resolution for formant frequency is about 1.5%. Minimal-uncertainty thresholds are similar to the most accurate discrimination previously reported in the F1 region, but about a factor of three lower (more precise) in the F2 region. Thresholds were also measured for one vowel, /I/, in a variety of consonantal contexts, /b, d, g, z, m, l/ (Kewley-Port and Watson, 1991). For F1 and F2, the resulting thresholds were a factor of about 4-5 smaller than those reported by Mermelstein (1978). Additional experiments estimated formant frequency thresholds under medium stimulus uncertainty (Kewley-Port, 1992). While training required longer to approach asymptote, and levels of performance were higher for some CVC's than for others, final thresholds were generally similar to those obtained for isolated vowels. Apparently, auditory acuity for formant frequency discrimination for well-trained subjects is generally the same for vowels in isolation and in CVC contexts, under both minimal and medium levels of stimulus uncertainty.

F. Partially Supported Projects.

1. *Auditory and Visual Speech Perception: Confirmation of a Modality-Independent Source of Individual Differences.* Watson, W. Qui, M. Chamberlain, S. Li.

Two experiments were run to determine whether individual differences in auditory speech recognition abilities are predictable from those for speechreading (lipreading), using a total of 90 normal-hearing college-student subjects. Tests included single words and sentences, recorded on a video disk by a male actor (Johns Hopkins Lipreading Corpus, Bernstein and Demorest, 1986). The auditory speech was presented with a white noise masker, at -7 dB Sp/N. The correlations between overall auditory and visual performance were 0.52 and 0.43 in the two experiments, suggesting the existence of a modality-independent ability to perceive linguistic "wholes" on the basis of linguistic fragments. Subjects in the second experiment also identified printed sentences, with 40-60% portions of the printed characters deleted. Performance on this "Fragmented-Sentences Test" also correlated significantly with auditory and visual speech recognition. The existence of a modality-independent source of variance in speech recognition abilities may be a partial explanation of the difficulty in demonstrating strong associations between psychoacoustic measures of spectral or temporal acuity, and speech discrimination or identification. [Additional support from AFOSR through the Institute for the Study of Human Capabilities.]

2. *The effects of training method on frequency discrimination for individual components of complex tonal patterns.* Robert F. Port, Catherine L. Rogers, Watson, Kidd

It has been assumed that subjects trained to detect increments in the frequency of all components of complex tonal patterns (broad focus) would be less accurate in detecting changes in a single target tone than subjects who have been trained to detect changes in only that component [e.g., Watson et al., J. Acoust. Soc. Am. 60, 1176--1186 (1976)]. In several experiments, using a number of 750-ms ten-tone patterns, subjects were trained using one of three methods: in the first two, a S/2AFC procedure was used to train subjects to detect frequency increments in a specific target tone (group one) or to detect frequency increments that could occur in any of the ten components (group two), and in the third, subjects were trained only to identify the individual patterns. Subjects trained using these methods were tested on their ability to detect changes in various components of the patterns, including the target tone for the first group. In all of these experiments, only very slight differences in performance were found among the different groups. These results suggest that lengthy experience with a given pattern allows a listener to discriminate small differences in frequency in any of the individual components of that pattern, relatively independent of the nature of that experience. [Additional support from ONR, R. Port Principal Investigator.]

G. New laboratory developments. Robinson and Rickert

During the Summer of 1993 the Auditory Research Laboratory in the Department of Psychology was completely reequipped. With primary support from Indiana University and additional support from AFOSR through the Institute for the Study of Human Capabilities, the old DEC PDP-11/34 system was replaced with a 486-based system using a Tucker-Davis array processor and Tucker-Davis audio equipment. The laboratory is designed to run four subjects simultaneously with separate control of the stimuli delivered to each subject.

Personnel

Name	Position Title	Department
Charles S. Watson, Ph.D.	Professor	Speech and Hearing Sciences
Donald E. Robinson, Ph.D.	Professor	Psychology
Gary R. Kidd, Ph.D.	Associate Scientist	Speech and Hearing Sciences
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Sheldon Li, Ph.D.	Research Associate	Speech and Hearing Sciences
Ward R. Drennan	Graduate Research Assistant	Speech and Hearing Sciences
Martin E. Rickert	Graduate Research Assistant	Psychology

Manuscripts and Publications

Coble, S. F., & Robinson, D. E. (1992). Discriminability of bursts of reproducible noise. The Journal of the Acoustical Society of America., 92, 2630-2635.

Kidd, G. R., & Watson, C. S. (1992): The "proportion-of-the-total-duration (PTD) rule" for the discrimination of auditory patterns. Journal of the Acoustical Society of America, 92, 3109-3118

Manuscripts in Preparation

Kidd, G.R. Proportional duration and proportional variance as factors in auditory pattern discrimination. Submitted to the Journal of the Acoustical Society of America.

Kidd, G. R., & Watson, C. S. Detection of frequency changes in transposed tonal patterns. (in preparation for J. Acoust. Soc. Am.)

Watson, C. S., Qui, W. W., Chamberlain, M., & Li, X. Auditory and Visual Speech Perception: Confirmation of a Modality-Independent Source of Individual Differences. Submitted to the Journal of the Acoustical Society of America.

Watson, C. S., & Kidd, G. R. (under revision). The perception of complex waveforms. In Crocker, M. J. (Ed.) Handbook of Acoustics. New York: Wiley.

Oral Presentations

Kidd, G. R., & Watson, C. S. (1992). The proportion of the total-duration (PTD) rule holds for duration discrimination. J. Acoust. Soc. Am., 92, Pt. 2, 2318.

Watson, C. S., Qui, W. W., & Chamberlain, M. (1992). Correlations between auditory and visual speech processing ability: Evidence for a modality-independent source of variance. J. Acoust. Soc. Am., 92, Pt. 2, 2385.

Watson, C. S., & Li, X. (1992). Effects of spectral and temporal uncertainty on the detection of increments in the level of individual tonal components of "profile" stimuli. J. Acoust. Soc. Am., 92, Pt. 2, 2319.

Kidd, G. R. (1993). Temporally directed attention in the detection and discrimination of auditory pattern components. J. Acoust. Soc. Am., 93, Pt. 2, 2315.

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Robinson, D. E. and Rickert, M. E. (1993). A stimulus-oriented model for discrimination of Gaussian noise samples, revisited (again), AFOSR Conference, Dayton, OH.

Watson, C. S., Kidd, G. R., Surprenant, A., & Drennan, W. R. (1993). Use of the psychophysical method of adjustment in tonal pattern discrimination. J. Acoust. Soc. Am., 93, Pt. 2, 2315.

Watson, C. S., Kidd, G. R., Surprenant, A., & Drennan, W. R. (1993). Properties of the structure of multi-tone sequential patterns that determine the difficulty of perceptually isolating single target components. J. Acoust. Soc. Am., 93, Pt. 2, 2315.